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6. AUTHORS
Professor Eyad Abed

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Maryland
College Park, MD 20742

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13. ABSTRACT *(Maximum 200 words)*

Research was conducted in five main areas:

(i) Nonlinear Dynamics of Compression Systems
(ii) Synthesis of Robust Nonlinear Controllers
(iii) Global Stability Analysis of Controllers
(iv) Modeling Enhancements
(v) Modal Participation and Instability Precursors

Results are described in the report along with the bibliography of published papers resulting from this grant.

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Final Technical Report

for AFOSR Grant Number F49620-93-1-0186

Active Control of Surge and Stall in Axial Flow Compressors

E.H. Abed, PI and R.A. Adomaitis, Co-PI
Institute for Systems Research
University of Maryland
College Park, MD 20742
abed@eng.umd.edu

Submitted to:

Dr. Marc Q. Jacobs
Directorate of Mathematical and Information Sciences
and Computational Mathematics
AFOSR/NM, 110 Duncan Ave., Suite B115
Bolling AFB DC 20332-0001

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OUTLINE

1. Overview of the Research Effort
2. Accomplishments/New Findings
3. Personnel Supported
4. Publications
5. Interactions/Transitions
6. Honors/Awards

FINAL TECHNICAL REPORT

This is the final report for AFOSR Grant Number F49620-93-1-0186, a three-year grant to the University of Maryland that started on March 1, 1993 and concluded, after a no-cost extension, on June 15, 1996. The grant, entitled "Active Control of Surge and Stall in Axial Flow Compressors," focused on modeling and control design issues for the nonlinear surge and rotating stall phenomena that can occur in axial flow compressors operated in the regimes of highest performance. The cognizant AFOSR Program Manager for the grant was Dr. Marc Q. Jacobs, of the Directorate of Mathematical and Information Sciences and Computational Mathematics. The Principal Investigator on the grant was Dr. Eyad H. Abed, a Professor in the Department of Electrical Engineering who holds a joint appointment with the Institute for Systems Research. Dr. Raymond A. Adomaitis, an Assistant Research Scientist with the Institute for Systems Research, was Co- Principal Investigator. (Recently Dr. Adomaitis accepted an appointment as Assistant Professor of Chemical Engineering at the University of Maryland.)

The technical report begins with a summary of the main goals of the project. Next, the main achievements are discussed. The remainder of the technical report gives information including personnel supported under the grant, publications benefiting from the grant, interactions and transitions, and honors and awards received by the co-PIs during the term of the grant.

1 Overview of the Research Effort

The goals of the research effort may be broadly divided into five categories, as follows. Note that the first four of these categories were in the original proposal, while the fifth was added during the second year of the effort. This fifth category was found to be beneficial to the control design aspects of the work.

(i) *Nonlinear Dynamics of Compression Systems.* This aspect of the research includes analytical and numerical study of the qualitative changes in the dynamical behavior of compression systems that occur as parameters are varied. This results in an understanding of both the instability mechanisms responsible for stall and surge inception, and the nonlinear growth to fully-developed surge and rotating stall.

(ii) *Synthesis of Robust Nonlinear Controllers.* This aspect of the research mainly involves application of bifurcation control techniques to active stall control design, allowing operation near peak pressure rise. It also involves extensions of bifurcation control results as needed.

(iii) *Global Stability Analysis of Controllers.* This goal of the research effort involves nonlinear stability analysis of models of controlled compression systems.

(iv) *Modeling Enhancements.* This phase of the research involves development of high-fidelity, multi-stage compression system models along with scalable solution algorithms suitable for massively parallel processors. Emphasis is placed on modeling techniques which provide a rational framework for generating reduced-order models useful for bifurcation analysis and control.

(v) *Modal Participation and Instability Precursors.* This phase of the research involves two related aspects: study of the participation of states in modes of instability, and algorithms for real-time detection of impending instability. In addition, it is important to apply these results to multistage compression system models, and to deduce implications for sensor and actuator placement in multistage compression systems.

2 Accomplishments/New Findings

The main accomplishments of the research project can be divided into results on modeling and and results on control of multistage compression systems. Moreover, the modeling results and the control design results both can be further viewed as numerical or analytical. Thus, detailed numerical models as well as less detailed analytical models were developed. The numerical models developed also include graphical display capabilities for illustration of the evolution of the gas flow field in a compression system. There are important and immediate benefits to the parallel development of numerical and analytical approaches for the analysis and control of compression systems. For example, it is very difficult to design a controller based on a numerical model of the dynamical system to be controlled, especially if the system is complex. However, availability of a less accurate analytical model that reflects the structure of the system and any fundamental nonlinearities can facilitate the design of a controller. The controller designed in this way can then be tested on the numerical model. In fact, the numerical model can be used to "tune" the control gains. This methodology can also be applied to an experimental set-up rather than a numerical model.

In the following, we list the main accomplishments of the research project.

1) We have developed a modeling approach unique in the field of turbocompressor simulation in that not only do the forcing functions depend on spatial position, but they are also computed solely from the equations of fluid motion and the geometry of the compressor blading. The simulation model developed was employed to study hysteresis in the compressor behavior. An important aspect of this work is studying the *predictive* capabilities of such a model in simulating the inception of rotating stall as the stall margin is crossed, and following the growth of these instabilities to fully-developed rotating stall. This work has shown that simulations of rotor blade wake momentum defect growth to a fully separated flow field blocking a blade passage is consistent with the conceptual model of compressor stall, originally proposed by Iura and Rannie (Trans. ASME, 1954). Stall cell propagation rates of approximately 1/2 rotor speed were observed in our simulations. The stall cell propagation mechanism put forth by the cited study is corroborated by our simulations. An important step towards understanding turbocompressor flow instability inception and control that has been completed in this work is the development of an accurate fluid dynamic model. Issues such as identification of the primary instability mechanism, determining whether the onset of instabilities can be detected, and comparisons of different control approaches (one-dimensional vs. "distributed" controls) can be resolved with models of sufficient fidelity.

Because of the complexity of multi-stage compression systems, direct modeling of flows at the individual rotor/stator blade-scale level is computationally impractical. Furthermore, dynamic models of such detail, even if computationally tractable, would not be amenable to theoretical analysis techniques used to gain insight into stall inception mechanisms, and certainly are not suitable for controller development.

Because of the limited predictive capabilities of compressor flow simulators in the past,

a large body of experimental data on compression system performance has accumulated. Theoretical understanding of the bifurcations responsible for compressor stall and surge has evolved in parallel with this experimental work. Our modeling work is meant to bridge the gap between the two, incorporating experimentally-determined correlations describing flow features too difficult to simulate from first principles, combined with rigorous flow modeling where possible. In the numerical modeling work, a consistent path to reduced-order models was always kept clear.

Computing a representative Reynolds number based the hub diameter length scale indicates that the flow through the compressor is highly turbulent This means compressor instabilities are transitions in the structure of the *time-smoothed* flow field. With this in mind, we see that a rational model of compressor flows can be based on averaging the Navier-Stokes equations over a length scale longer than the turbulent fluctuations and shorter than the large-scale structures. The dynamics of large-scale structures depend on compression system geometry and other specific characteristics; the small-scale, energy dissipating structures are more universal and so closure of the averaged Navier-Stokes is provided by a subgrid modeling technique.

To overcome the computational infeasibility of detailed simulation of the fluid flow dynamics at individual blade levels in multistage compressors, we approximate the power input to the fluid flow field in each stage by forcing functions to the fluid equations of motion. These data are available in the form of experimentally-determined stage-by-stage performance curves. This modeling approach forms the basis of the joint experimental/simulation research outlined in the Cooperative Research and Development Agreement between the University of Maryland and Army Research Office Vehicle Propulsion Directorate. The goals of this project are to understand flow instabilities in the seven axial, single centrifugal stage T-55 compressor and development of a stability augmentation system.

In the CFD-based modeling discussed above, the power input forcing functions were defined for each rotor and stator row. If we spread the forcing functions over the entire compressor section and make further simplifying assumptions on the turbulence modeling and size of flow perturbations, we can reduce the model to a single partial differential equation. Analysis of this reduced system by linearized stability analysis and weakly nonlinear methods is possible. The findings of this analysis demonstrate that a sequence of bifurcations corresponding to stalled flows of different cell numbers takes place along the uniform flow solution branch. The first of these stall inception instabilities is a subcritical bifurcation. Secondary bifurcations render this flow pattern stable, leading to a hysteresis loop.

2) The simulation model developed was employed to study hysteresis in the compressor behavior. In the model, the throttle was closed through the range where the flow was found to become unstable. Simulation showed the onset of stall soon afterwards. The disturbance was found to grow to a large-amplitude rotating stall cell after only a few rotor revolutions, growing only out of the natural flow asymmetry induced by the rotor-stator blade interactions. After a period of disturbance growth to fully developed rotating stall, the throttle opening was returned to its original size, which had initially corresponded to a *locally* asymptotically stable uniform flow operating point. After reaching equilibrium, we found that the rotating stall persisted, a clear indicator of multistability (hysteresis).

3) At the inception of instability or stall in a multistage compression system, one would expect that not all stages participate equally in the instability. It is important to determine the stage or stages that are most impacted by the instability. One main reason for this

is that such knowledge is useful for actuator placement. Actuators are best placed in the physical neighborhood of an instability onset.

We have applied Selective Modal Analysis (SMA) to this issue. SMA was originally introduced in the electric power systems field, where it has been useful in determination of the physical nature of modes of instability (e.g., electrical vs. mechanical). It has also proved useful in order reduction, and in sensor and actuator placement issues. In this technique, each mode of a dynamic system is related to subsystem modes, and thus to state variables of the system. The method results in numerical indices, called participation factors, that indicate the degree to which any state variable participates in a system mode. This feature allows determination of the participation of each stage in an overall compression system mode. The main application is to determination of the stage(s) most involved in a mode of instability, with the associated implications for control design. Particularly important among these are implications for actuator placement. For example, insights can be obtained into which bleeds or variable stator blade rows to actuate.

4) Besides applying SMA (in particular participation factors) to multistage compression system models, we have also re-examined the concept of participation factors and given a derivation of the expression for these quantities based on a new first-principles definition. This is useful not only from a conceptual perspective, but also as a basis for extending this useful method to nonlinear problems and in other useful directions.

5) We have introduced the use of "precursor signals" into the study of multistage compression system instability. Precursors were originally studied by Weisenfeld as a tool for understanding the amplification of noise in systems near bifurcation points. We have expanded this notion to address system monitoring and signal processing techniques that result in a "warning signal" that appears when system parameters drift dangerously close to critical (bifurcation) values. Past these critical values of the system parameters, the system operating condition will likely lose stability, corresponding to stall. The availability of a reliable precursor signal is thus very important in the safe operation of a physical system the model for which is highly uncertain. Further work on precursors usin higher order spectral analysis also was undertaken and this work continues in a new grant from AFOSR.

6) We have coupled the work on precursors with the SMA approach mentioned above, resulting in a method for deciding the best location for placing sensors for continuous monitoring of a multistage compression system. Briefly, it was found that compression system stages whose variables have high participation factors provide significantly larger precursor signals as compared to other stages.

7) We have continued our investigations of control of systems with bifurcations with application to axial flow compressors. Having shown that stall inception takes place by means of a subcritical bifurcation near peak pressure rise, we can define the control problem as one of reducing the hysteresis loop to improve operability. This type of control effectively reduces the "nonlinear" stall margin defined by the range of multistability. Using the analytical multistage models and the numerical reduced-order models, we have developed stall suppression methods by direct control of the instability inception bifurcations. Further refinements of the stall controllers, such as the benefits of nonsmooth controls, have been investigated.

We have also analyzed controller-induced oscillations found in experiments at United Technologies Research Center (UTRC). These oscillations occur when a basic bifurcation control law proposed by our group is applied in high speed compressors. The UTRC researchers then modified the control law to alleviate these oscillations. We have studied the

reasons for the occurrence of the oscillatory behavior and means for alleviating it analytically. This analytical study makes use of tools from bifurcation theory and singular perturbation theory. Briefly, we have shown that as the compressor speed parameter (Greitzer's B-parameter) is increased, the system differential equations become singularly perturbed and a Hopf bifurcation that occurs on the bifurcated equilibrium solution moves arbitrarily close to the original bifurcation point.

We have also developed a control design approach using the harmonic balance method. We have given explicit calculations for approximate determination of Hopf and period doubling bifurcation points in nonlinear systems, and for determination of the effect of control action on these bifurcations. Other papers in the list of publications address further applications of bifurcation control to convection and power systems and to the control of chaos.

8) We have contributed to the limited and relatively new literature on the control of systems with bifurcations by writing several review articles on the subject, one of which appears in the recently published Control Systems Handbook from CRC Press. These articles, which are written for a general control systems audience, are expected to help increase the understanding of the role of bifurcations and nonlinear dynamics in control system analysis and design. We have also prepared a set of lecture notes on the subject that has been used in a graduate special topics course at the University of Maryland as well as at special workshops in Italy (University of Florence) and Taiwan (National Chiao-Tung University). These notes are being revised to prepare them for publication in book form.

3 Personnel Supported

The following individuals have received support and/or been associated with this this grant: Dr. Eyad H. Abed (Professor and PI), Dr. Raymond A. Adomaitis (Assistant Research Scientist and co-PI; Now also an Assistant Professor), Mr. Taihyun Kim (Ph.D. Candidate), Dr. Bertina Ho-Mock-Qai (Completed Ph.D. in 1996), Mr. Hassan Yaghoobi (Ph.D. Candidate), Mr. Chung-chieh Fang (Ph.D. Candidate), Mr. Mahir Nayfeh (Ph.D. Candidate), and Mr. David Lindsay (Ph.D. Candidate).

4 Publications

[1] Abed, E.H., *Feedback Control of Bifurcations and Chaos in Dynamical Systems*, Lecture Notes, University of Maryland, College Park, 1995.

[2] Abed, E.H., H.O. Wang and A. Tesi, "Control of Bifurcations and Chaos," *The Control Handbook*, W.S. Levine, Editor, Sec. 57.6, pp. 951-966, Boca Raton: CRC Press, 1996.

[3] Abed, E.H. and H.O. Wang, "Feedback Control of Bifurcation and Chaos in Dynamical Systems," in *Nonlinear Dynamics and Stochastic Mechanics*, W. Kliemann and N. Sri Namachchivaya, Eds., pp. 153-173, Boca Raton: CRC Press, 1995.

[4] Abed, E.H., "Bifurcation control with applications," invited paper for the journal *Chaos*, in preparation, 1996.

[5] Abed, E.H.,"Control of Nonlinear Systems Near Fold Bifurcations," presented at the *Mathematical Theory of Networks and Systems (MTNS) Symposium*, Regensburg, Germany, August 1993 (invited).

[6] Abed, E.H., B. Ho-Mock-Qai and T. Kim, "Modal Participation in the Stability Analysis and Control of Multistage Compression Systems," in *Sensing, Actuation, and Control in Aeropropulsion*, J.D. Paduano, Ed., Proc. SPIE 2494, pp. 186-195, 1995.

[7] Abed, E.H., "Compressor Stall Precursors as Indicators of Impending Instability," *34th IEEE Conference on Decision and Control*, New Orleans, Dec. 1995, presented (invited).

[8] Abed, E.H., "Precursors for Nonlinear Instabilities," *1995 AFOSR Grantees/Contractors Meeting in Dynamics and Control*, Minneapolis, 5-7 June 1995.

[9] Abed, E.H., "Detection of Incipient Instability in Uncertain Systems," *Fourth IEEE Conference on Control Applications*, Albany, New York, September 28-29, 1995, presented (invited). Related paper on "A New Approach to Modal Participation" co-authored with D. Lindsay is in preparation.

[10] Abed, E.H., "Bifurcation-Theoretic Issues in the Control of Voltage Collapse," in *Systems Control Theory for Power Systems*, IMA Volumes in Mathematics and Its Applications, Vol. 64, J.H. Chow, P.V. Kokotovic and R.J. Thomas, Editors, pp. 1-21, New York: Springer-Verlag, 1995.

[11] Abed, E.H., Y.-S. Chou, A. Guran and A.L. Tits, "Nonlinear Stabilization and Parametric Optimization in the Benchmark Nonlinear Control Design Problem," in *Proc. 1995 American Control Conference*, Seattle, June 21-23 1995 (invited).

[12] Abed, E.H., "Review of the 2nd Edition of *Nonlinear Systems* by M. Vidyasagar," *IEEE Trans. Automatic Control*, Vol. 39, No. 7, p. 1535, July 1994 (solicited).

[13] Adomaitis, R.A., "Spatially Resolved Compressor Characteristics for Modeling and Control of Blade-Scale Flow Instabilities," in *Sensing, Actuation, and Control in Aeropropulsion*, J.D. Paduano, Ed., Proc. SPIE 2494, pp. 36-46, 1995.

[14] Adomaitis, R.A., "Multistage Compressor Models for Stall Detection and Control," in *Proc. 34th IEEE Conference on Decision and Control*, New Orleans, Dec. 1995 (invited).

[15] Adomaitis, R. A. and E. H. Abed, "Bifurcation Analysis of Nonuniform Flow Patterns in Axial-Flow Gas Compressors," in *Proc. 1st World Congress of Nonlinear Analysts*, 1996.

[16] Adomaitis, R.A. and E.H. Abed, "Local Nonlinear Control of Stall Inception in Axial Flow Compressors," *Proceedings of the 29th AIAA/SAE/ASME/ASEE Joint Propulsion Conference and Exhibit*, Monterey, CA, June 28-30, 1993 (AIAA Paper 93-2230).

[17] Adomaitis, R. A. and E. H. Abed, "Local Nonlinear Control of Stall Inception in Axial Flow Compressors," accepted with revision to *ASME J. Propulsion and Power.*

[18] Adomaitis, R. A., "Analysis of Turbocompressor Flow Instabilities," *1994 Annual SIAM Meeting*, San Diego, CA, July 1994, presented.

[19] Fu, J.-H. and E.H. Abed, "Linear Feedback Stabilization of Nonlinear Systems with an Uncontrollable Critical Mode," *Automatica*, Vol. 29, No. 4, pp. 999-1010, July 1993.

[20] Genesio, R., A. Tesi, H.O. Wang and E.H. Abed, "Control of Period Doubling Bifurcations using Harmonic Balance," *Proc. 32nd IEEE Conference on Decision and Control*, San Antonio, TX, Dec. 1993, pp. 492-497 (invited).

[21] Genesio, R., M. Basso, E.H. Abed and A. Tesi, "On Stabilizing Limit Cycle Bifurcations in Continuous Feedback Systems," in *Proc. European Conf. Circuit Theory and Design (ECCTD'95)*, Istanbul, Turkey, August-September 1995.

[22] Kafri, W.S. and E.H. Abed, "Stability Analysis of Discrete-Time Singularly Perturbed Systems," *IEEE Transactions on Circuits and Systems—I: Fundamental Theory and Applications*, Vol. 43, No. 10, pp. 848-850, October 1996.

[23] Liaw, D.-C. and E.H. Abed, "Active Control of Compressor Stall Inception: A Bifurcation-Theoretic Approach," *Automatica*, Vol. 32, No. 1, pp. 109-115, January 1996.

[24] M.A. Nayfeh, "Bifurcation Control of Singularly Perturbed Systems with Application to Active Stall Control of Compression Systems," Ph.D. Dissertation, Dept. of Electrical Engineering, University of Maryland, College Park, to be submitted in Spring 1997.

[25] Saydy, L., Y.-S. Chou, A.L. Tits and E.H. Abed, "Enlarging Stability Domains by State Feedback using LMIs," presented at the *1994 American Control Conference*, Baltimore, MD, June 1994.

[26] Tesi, A., E.H. Abed, R. Genesio and H.O. Wang, "Harmonic Balance Analysis of Period Doubling Bifurcations with Implications for Control of Nonlinear Dynamics," *Automatica*, accepted for publication, 1996.

[27] Wang, H.O., R.A. Adomaitis and E.H. Abed, "Active Stabilization of Rotating Stall in Axial-Flow Gas Compressors," *Proceedings of the 1993 IEEE Regional Conference on Aerospace Control Systems*, Thousand Oaks, CA, May 25-27, 1993, pp. 498-502.

[28] Wang, H.O., R.A. Adomaitis and E.H. Abed, "Nonlinear Analysis and Control of Rotating Stall in Axial Flow Compressors," *Proc. 1994 American Control Conference*, Baltimore, MD, June 1994, pp. 2317-2321.

[29] H. Wang and E.H. Abed, "Bifurcation Control of Chaotic Dynamical Systems," in *Coping with Chaos*, E. Ott, T. Sauer and J.A. Yorke, Editors, pp. 328-333, New York: Wiley, 1994.

[30] Wang, H.O. and E.H. Abed, "Bifurcation Control of a Chaotic System," *Automatica*, Vol. 31, No. 9, pp. 1213-1226, September 1995.

[31] Wang, H.O. and E.H. Abed, "Control of Period Doubling Bifurcations and Chaos," *Proc. 33rd IEEE Conference on Decision and Control*, Orlando, FL, Dec. 1994, pp. 3287-3292.

[32] Wang, H.O. and E.H. Abed, "Control of Routes to Chaos," presented at the *Symposium on Nonlinear Dynamics and Stochastic Mechanics*, Fields Institute for Research in the Mathematical Sciences, Waterloo, Canada, Aug.-Sept. 1993 (invited).

[33] Hua O. Wang, "Control of Bifurcations and Routes to Chaos in Dynamical Systems," Dept. of Electrical Engineering, Inst. for Systems Research Tech Rept No. Ph.D. 93-10, University of Maryland: December 1993.

5 Interactions/Transitions

1) In the final year of the grant, an AFOSR "Monthly Miracle" article was prepared in cooperation with the Program Manager (Dr. Marc Jacobs) and with Dr. Carl Nett of UTRC. The article later appeared in the annual publication "AFOSR Research Highlights." The article describes the transition of a compressor control concept from this group to industry.

2) An invited talk entitled "Intelligent Control Issues for PEBB-Based Systems" was given by E.H. Abed at the *ONR-Virginia Tech Control Technology Workshop: The Regulation and Distribution of Power in Large Systems*, held at the Virginia Center for Innovative Technology, Herndon, VA, 24-25 April 1995. The nonlinear dynamics issues that may arise in networks of PEBBs (power electronic building blocks) that ONR has set as a research goal were discussed. Some of the lessons learned in the current grant were communicated.

3) A talk entitled "Precursors for nonlinear instabilities," was given at the *1995 AFOSR Grantees/Contractors Meeting in Dynamics and Control*, held in Minneapolis during 5-7 June 1995.

4) A Cooperative Research and Development Agreement with the Army Vehicle Propulsion Directorate at NASA's Lewis Research Center is in place. This agreement is for the joint development of a CFD model of the eight-stage axi-centrifugal compressor for the T55 compressor, found in the turboshaft engine which powers the Army's Chinook helicopter. This dynamic model will be used in developing and simulating stall controllers for the T55.

5) There has been significant interaction with Dr. Wishaa Hosny of General Electric Aircraft Engines on multistage compression system modeling. Discussions have also taken place with researchers from Wright-Patterson Air Force Base and United Technologies Research Center. There was also regular communication with the engineering staff of Textron-Lycoming. Possible uses of the ideas developed in this project for control of combustion instabilities and for turbine modeling and control are being discussed with industrial researchers.

6) Some of the ideas, analysis techniques, and simulation packages developed in the context of stall control research carry over to materials manufacturing process control. This is a growing area of research at the Institute for Systems Research, and collaborative work has been initiated with the Materials Directorate at WPAFB, NRL, North Carolina State University, and other academic and government laboratories.

7) Compressor control problems have been discussed with faculty of other universities working in this area.

8) Dr. Abed co-organized a Workshop on Nonlinear Control and Control of Chaos that was held at the International Centre for Theoretical Physics in Trieste, Italy, during June 17-28, 1996. The workshop brought together leading researchers in the area of control of nonlinear dynamics to promote cross-fertilization of ideas from the engineering and science disciplines. At the workshop, Dr. Abed gave a lecture entitled "Control of Nonlinear Dynamics in Engineering Systems."

6 Honors/Awards

During the term of the grant, the Principal Investigator (Eyad H. Abed) was the recipient of the following honors and awards:

1. The O. Hugo Schuck Best Paper Award was received in 1994 by Dr. Eyad H. Abed. The awarding organization was the American Automatic Control Council.

2. Listed in the biographical collections *American Men and Women of Science*, *Who's Who in Technology*, and *Who's Who in Science and Engineering*.